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A Schumpeter-inspired Approach to the Construction of R&D Capital Stocks

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Abstract

A new method for constructing R&D capital stocks is proposed and tested. Following Schumpeter, the development of R&D capital stocks is modelled as a process of creative destruction. Newly generated knowledge is assumed not only to add to the existing R&D capital stocks but also, by displacing old knowledge, to destroy part of that capital. This is in stark contrast to the perpetual inventory method, which postulates a constant rate of depreciation. We compare both methods by estimating the impact of R&D and spillovers on output of nine industries in twelve OECD countries, and find that the new approach leads to more sensible and robust results.

Keywords: R&D capital stocks, knowledge spillovers, creative destruction

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1 Introduction

Physical capital stocks have been the subject of longstanding debate, and the controversy over their proper measurement continues to this day. In the case of R&D capital stocks, however, the discussion has been very limited, and today the perpetual inventory method (PIM) is considered the state of the art for constructing them.

An examination of literature on productivity and knowledge spillovers – the main application for R&D capital stock measures – shows an uptick in methodological discussions. Although the number of empirical studies on knowledge spillovers has increased substantially in recent years, they yield a somewhat ambiguous picture of the estimated rates of return on internal and external R&D (Mohnen, 1996 and Griliches, 1995).[1] Coe and Helpman (1995), Verspagen (1997a, 1997b), Keller (1998), Kao, Chiang and Cheng (1999), Atella and Quintieri (2001) and Edmond (2001) show that the estimation results on the rates of returns on internal and external R&D depend heavily on how the estimation equation is specified, which econometric method is applied, and which technology-proximity measures are used for the construction of external R&D capital stocks. While these aspects have been discussed extensively in the literature (e.g. Keller, 1999, 2001; Kao, Chiang and Cheng, 1999 and Edmond, 2001), the question of the adequacy of the perpetual inventory method (PIM) for the construction of R&D capital stocks has not been discussed in depth since Griliches (1979, 1992).[2]

The lack of attention to the construction of R&D capital stocks is surprising considering that some of the problems observed in determining the rates of return on internal and external R&D could be attributable to the construction method. Indeed, this suspicion is nurtured by the fact that the PIM was developed for constructing physical capital stocks (Goldsmith, 1951; Jorgenson, 1963 and Hulten, 1991). Using the PIM to construct R&D capital requires the assumption that the

[1] Only a part of the differences can be explained by different data sources and aggregation levels used.

[2] Only a few studies have recently addressed the problem of determining the depreciation rate (Nadiri and Prucha, 1996), the gestation lag (Esposti and Pierani, 2003) and the impact of the assumed depreciation rate on the estimation results (Hall and Mairesse, 1995).

R&D capital stock development follows the same mechanism as physical capital, which implies that knowledge is lost with the passage of time. Schumpeter (1934, 1942), Machlup (1962), Schmookler (1966), and Nordhaus (1969) have already discussed the characteristics of knowledge that set it apart from physical capital, i.e. the fact that knowledge is lost when replaced by new knowledge.

Bitzer (2005) suggests a new construction method for R&D capital stocks based on Schumpeter's notion of creative destruction. In this paper we label this new approach the 'Schumpeter-inspired method' (SIM). It is based on the assumption that knowledge becomes obsolete through the emergence of new knowledge and therefore links the depreciation of the R&D capital stock to past investments in R&D. Bitzer (2005) tests the sensibility of the new method with regard to the assumed lag structure and the assumed displacement rate. However, the question whether the new method leads to more robust results than the PIM when both are applied to the same data set has been left to further research. It is the purpose of this paper to fill this gap by carrying out a direct comparison of the SIM and the PIM by estimating the rates of return on internal, external domestic and external foreign R&D capital stocks constructed either with SIM or PIM using the same data set.

Furthermore, our paper extends the analysis of Bitzer (2005) in three ways: first, we control for size effects by carrying out the estimations in labor intensities. Second, we explicitly address the often suspected problems of multicolinearity between the different R&D capital stock variables by examining the variance decomposition proportions of the characteristic roots. Third, we test the sensibility of the results with respect to the applied estimation method. Therefore, in a first step the estimations are carried out with simple OLS and panel corrected standard errors (PCSE, Beck and Katz 1995). In a second step the estimations are repeated using a Feasible Generalised Least Squares (FGLS) estimator with group-specific variances, leading to efficient estimators, i.e. less restrictive hypothesis tests.

We obtain more reasonable results in terms of significance and robustness in the econometric analysis for the series constructed using the SIM than for those using the PIM.

This paper is organized as follows. Section 2 discusses the assumptions and drawbacks of the commonly used PIM method for constructing R&D capital stocks. Section 3 expounds the Schumpeter-inspired method. Section 4 describes the empirical implementation. Section 5 presents the estimation results for the rates of return on internal and external R&D using different R&D capital stock variables constructed either with PIM or SIM. Section 6 concludes the paper.

2 Constructing R&D capital stocks using the Perpetual Inventory Method (PIM)

In the late fifties, when Griliches (1958) became one of the first to estimate the influence of R&D on productivity and output development, the need emerged for a measure of technological knowledge. The PIM lent itself to the construction of R&D capital because it offers an applicable procedure that accounts for the depreciation of knowledge, a necessary condition for a plausible R&D capital measure.

In studies estimating the influence of R&D on productivity and output, the PIM is employed widely[3] today for calculating R&D capital stocks (e.g. Coe and Helpman 1995, Frantzen 1998, Park 2004). The construction of the R&D capital stock in these studies is based on a simple form of the PIM using the following well-known equation:

$$K_t = \lambda_0 I_t + \lambda_1 I_{t-1} + \cdots + \lambda_T I_{t-T} \quad \text{with} \quad 0 < \lambda \leq 1, \tag{1}$$

where λ is the share of knowledge of the corresponding vintage which is still used in production at time t, and T denotes the age of the oldest surviving vintage of R&D investments I. However, the share of obsolete knowledge in past vintages of R&D cannot be observed directly. Therefore, an assumption must be made about the depreciation of knowledge. It is common practice to assume a geometric depreciation of knowledge; i.e. $\lambda_0 = 1, \lambda_1 = (1-\delta), \lambda_2 = (1-\delta)^2, \cdots, \lambda_T = (1-\delta)^T$. Performing the Koyck transformation, equation 1 can be simplified to:

$$K_t = I_t + (1-\delta)K_{t-1}, \quad \text{with} \quad \delta = \frac{\lambda_{\tau-1} - \lambda_\tau}{\lambda_{\tau-1}}, \tag{2}$$

[3]Based on the work of Terleckyi (1974, 1980) a small number of studies use R&D expenditures or R&D intensities as a proxy for the R&D capital stock.

where δ is the depreciation rate which is assumed to be constant over time. Usually a value between 5 and 15 percent is taken for δ.

On the one hand, it is recognized that the assumption of a constant depreciation rate of knowledge is crucial for the applicability of the PIM. On the other hand, this assumption is the Achilles' heel of the PIM. While it may be appropriate for the construction of physical capital stocks (although controversy surrounds even this point: see Meinen, Verbiest and de Wolf, 1998; OECD, 2001), in the case of the construction of R&D capital stocks, the assumption of a constant depreciation rate is inappropriate. Nevertheless the PIM is the most common way of constructing R&D capital stocks today, despite the fact that it has little intuitive appeal with respect to the depreciation of knowledge (Mohnen, 1996; Griliches, 1995).

A constant depreciation rate implies that depreciation takes place in a mechanical way: independently of whether R&D is carried out or not, every year a constant percentage of the R&D capital stock becomes obsolete. A consequence of this modelling is that if all R&D stops, the R&D capital stock converges in the long run to zero. Following this thought through to its logical conclusion suggests that, in the final reckoning, mankind would revert back to the stone age if R&D were stopped completely.

We argue, however, that knowledge does not depreciate through use the way machines do, but instead becomes obsolete with the creation of new knowledge that displaces the old. This of course means that more (or less) R&D leads to a higher (or lower) depreciation. The actions of agents performing R&D therefore determine the depreciation of knowledge. Thus, the assumption that a certain constant percentage of existing knowledge is displaced every year is a serious drawback of the PIM.

3 A Schumpeter-Inspired Method (SIM)

Following Bitzer (2005), we suggest a new method for constructing R&D capital stocks which takes the particular characteristics of knowledge into account. According to the ideas of Schumpeter (1934, 1942), the development of R&D capital stocks is modelled as a process of creative destruction. The development of R&D capital stocks consists of two elements: the process of knowledge creation, which increases the R&D capital stock, and the process of knowledge destruction/displacement, which reduces the existing R&D capital stock.

The process of knowledge creation occurs when R&D is carried out. It is assumed that knowledge creation is a continuous process that takes place constantly during the life of an R&D project. Therefore the R&D capital stock increases continuously as long as R&D is carried out. The newly generated knowledge becomes effective when it enters the decision-making process of enterprises.

Generated knowledge can be approximated by R&D expenditure. As the R&D capital stock increases with *every* R&D project that is carried out, *all* past investments in R&D are included in the R&D capital stock measure. Considering this, the creation process is a simple accumulation of past investments in R&D, i.e. $\sum_{\tau=0}^{\infty} R_{t-\tau}$, where R denotes R&D expenditure.

On the other hand, the process of destruction reflects the fact that knowledge becomes obsolete as new knowledge emerges and displaces old knowledge. But implementing new knowledge takes time, and the destruction/displacement process does not take place instantly, but occurs with a lag. The depreciation of knowledge is assumed to follow a one-hoss-shay process (Hulten, 1991). Thus, knowledge does not wear out but vanishes from the R&D capital stock all at once when it is no longer used.

Similar to the creation process, the destruction process can be approximated by R&D expenditure, because the same R&D projects, which at first increase the R&D capital stock, reduce it with a time lag because of the displacement of old knowledge. Hence, current R&D investments displace the old R&D investments at some time in the future.[4] Nevertheless, new and old knowledge are not perfect substitutes. This means that current R&D activity has to be weighted with a displacement factor θ (with $0 < \theta < 1$), which captures the substitution rate of newly generated knowledge for old. The depreciation of old knowledge can thus be approximated via the displacement factor by current R&D expenditures. The destruction/displacement

[4]Please note that there are other external factors which might lead to a depreciation of the R&D capital stock and therefore our approximation of the R&D capital stock might be to high. Examples of such external factors are the oil price shock in the seventies as pointed out by Sterlacchini (1989), the transformation in Eastern Europe, or changes in the legislation as pointed out by Bitzer (2005).

process can therefore be written as follows: $-\sum_{\tau=k}^{\infty} \theta_{t-\tau} R_{t-\tau}$, with $k > 0$.

Collecting the terms for the processes of knowledge creation and destruction, the development of the R&D capital stock can be described with the following equation:

$$W_t = \sum_{\tau=0}^{\infty} R_{t-\tau} - \sum_{\tau=k}^{\infty} \theta_{t-\tau} R_{t-\tau} \quad \text{with} \quad k > 0; 0 < \theta < 1, \tag{3}$$

where W_t denotes the R&D capital stock at time t. Equation 3 shows that every R&D investment first induces an increase in the R&D capital stock, but thereafter renders a part of the existing R&D capital stock obsolete. Thus, the depreciation rate depends on the past investments in R&D and is therefore not constant as in the PIM. Furthermore, the dependency of the depreciation rate on past R&D investments yields the desirable result that the R&D capital stock converges to a positive constant if R&D ceases.

The substitution rate θ cannot be observed directly. However, a further assumption makes it possible to estimate it econometrically. Taking into consideration that in industrialized countries the majority of R&D projects aim at further developing existing technologies and products, and that ground-breaking innovations are rare, it is a plausible assumption that θ does not vary over time. Note that this assumption does *not* cause a constant depreciation rate.[5] Equation 3 can therefore be simplified as follows:

$$W_t^{'} = \sum_{\tau=0}^{\infty} R_{t-\tau} - \theta \sum_{\tau=k}^{\infty} R_{t-\tau} \quad \text{with} \quad k > 0; 0 < \theta < 1. \tag{4}$$

According to (4) the displacement rate θ can be estimated by using a production function approach and applying non-linear estimation methods. We perform this exercise in the next section.

4 Empirical Implementation

Calculating R&D capital stocks with PIM and SIM

To test the two methods, we use an extended production function approach to measure the impact of R&D on output (Verspagen, 1997a). The estimations and

[5]The depreciation rate of the R&D capital stock can be obtained by setting the investments in R&D to zero. Thus, $\frac{W_t^{'}}{W_{t-1}^{'}} = 1 - \frac{\theta R_{t-2}}{W_{t-1}^{'}}$. The right-hand term is obviously not constant.

therefore the calculations of the R&D capital stocks are carried out for 12 OECD countries using data for nine manufacturing sectors from 1975 to 1997. A detailed description of the data is given in the Appendix.

To calculate the different R&D capital stocks according to equations (2) and (4) several assumptions must be made. For the PIM method, according to (2), a depreciation rate δ of 10 percent is used, which is in line with most studies.[6] The initial stocks at time t_0 are calculated using the well-known procedure reported in Hall and Mairesse (1995) under the assumption of an annual growth rate for R&D expenditures of 2.5 percent.

For the SIM according to (4), we assume a time lag of two years ($k = 2$) for displacement.[7] This is in accordance with the findings of Pakes and Schankerman (1984, p. 82-84) and also Ravenscraft and Scherer (1982) on the average implementation lag of new inventions. A major advantage of the SIM is that it enables us to estimate the displacement rate θ. Using a Cobb-Douglas production function in labour intensities and applying a non-linear OLS we obtain the following results for θ:

$$\begin{aligned}\ln(Q_{it}/L_{it}) = \alpha_i + 0.013 \ln \left[\left(\sum_{\tau=0}^{1} R_{i,t-\tau} + (1 - 0.9387) \sum_{\tau=2}^{\infty} R_{i,t-\tau} \right) / L_{it} \right] \\ + 0.059 \ln(K_{it}/L_{it}) - 0.01 \ln L_{it} + 0.795 \ln(M_{it}/L_{it}) + 0.003t. \qquad (5)\\ n = 2016, \qquad R^2 = 0.997\end{aligned}$$

where Q_{it} is output, L_{it} is labor, K_{it} is physical capital, M_{it} is material / intermediate inputs, $R_{i,t}$ are R&D expenditures and t is a time trend. All parameters except $\ln L_{it}$ are significant at a 5 percent level. The highly significant group-specific (i.e. sector- and country-specific) fixed-effects α_i are not reported. The estimated average displacement rate is therefore 93.8 percent.[8] This implies that only 6.2 percent of knowledge generated is fundamentally new and therefore cannot substitute

[6]Further estimations with depreciation rates of 5, 15, and 20 percent have been carried out as well. The results are not significantly different from those reported later in this paper.

[7]In Bitzer (2005) the sensitivity of results with respect to the specification of different time lags is tested. The results turn out to be quite robust with respect to the variation of time lags.

[8]The sensibility of the SIM referring to the substitution rate was tested in Bitzer (2005). Estimations with substitution rates of 0.95, 0.90, or 0.80 did not produce significantly different results.

for older knowledge. The initial stocks at time t_0 are derived from the R&D expenditure at time t_1 by assuming an annual growth rate of 2.5 percent for R&D expenditures for $t \rightarrow -\infty$.

In studies measuring the impact of R&D it is the state of the art to consider not only internal R&D but also the R&D carried out by external actors from whom an enterprise, sector or country benefits in the form of knowledge spillovers (Verspagen, 1997a; Coe and Helpman, 1995; Keller, 1998). In the estimations carried out later in this paper we take into consideration two external R&D capital stocks: an external *domestic* R&D capital stock and an external *foreign* R&D capital stock.

Of course the two external R&D capital stocks also have to be constructed for PIM and SIM. Based on the internal R&D capital stocks, the external R&D capital stocks are constructed using the following procedure. The external *domestic* R&D capital stock (S^D_{it}) includes all R&D capital stocks of the other domestic sectors with exception of the R&D capital stock of the sector studied. For sector j in country c at time t the external *domestic* R&D capital stock is calculated as $S^D_{cjt} = \sum_{i=1}^{N} W'_{cit}$, with $i \neq j$. Similarly, the external *foreign* R&D capital stock (S^F_{it}) consists of the R&D capital stocks of all other countries with the exception of the R&D capital stock of the country studied. For country h at time t the external *foreign* R&D stock is calculated from $S^F_{ht} = \sum_{c=1}^{M} \sum_{i=1}^{N} W'_{cit}$, with $c \neq h$, where M is the number of countries and N is the number of industry sectors. Taking into consideration the recent critiques of the use of Technology Proximity Matrices (TPM) (Keller, 1998; Verspagen, 1997a, 1997b; Edmond, 2001), we refrain from using TPM weights to calculate the external R&D capital stocks. Thus our estimates use three R&D capital stocks – internal, external domestic and external foreign – each calculated both by PIM and by SIM.

Estimation methods

We conduct a sensitivity analysis by estimating the impact of internal, external domestic and external foreign R&D on output. As already mentioned, the latter two constitute an approximate representation of the influence of spillover effects. In addition to the commonly specified input factors labor, capital, internal R&D, external domestic R&D and external foreign R&D, we introduce material/intermediate inputs into the production function to separate the impact of rent spillovers from that of pure knowledge spillovers (Griliches, 1979, 1992). The following logarithmic Cobb-Douglas production function is the basis for our empirical assessment[9]

$$\ln(Q_{it}/L_{it}) = \alpha_i + \beta_1 \ln(W'_{i,t-1}/L_{it}) + \beta_2 \ln(S^D_{i,t-1}/L_{it}) + \beta_3 \ln(S^F_{i,t-1}/L_{it}) + \beta_4 \ln(K_{it}/L_{it}) + \beta'_5 \ln L_{it} + \beta_6 \ln(M_{it}/L_{it}) + \beta_7 t + \nu_{it}, \quad (6)$$

where Q_{it} is output, L_{it} is labor, K_{it} is physical capital, M_{it} is material / intermediate inputs and t is a time trend. It is worth noting that $\beta'_5 = (\beta_1+\beta_2+\beta_3+\beta_4+\beta_5+\beta_6-1)$, where β_5 is the elasticity of labor with respect to output that would be obtained in a specification of (6) without the substraction of $\ln L_{it}$ from both sides of the equation. Thus, returns to scale are not restricted in this specification. The parameter estimate β'_5 provides a direct method for testing whether or not returns to scale are constant. If β'_5 is not significantly different to zero, then the null of constant returns to scale is not rejected.

It should be noted that in (6) R&D capital stocks W', S^D and $S^F$are lagged one year in order to account for the delay between the time when R&D is performed and when it begins to affect production.[10] Thus, we assume that the lagged stocks are predetermined variables so that no instrumental variable estimation is required. Our estimations show that the internal R&D capital stock W' without any time lag is indeed not significant. For the external stocks, the time lags imply that the diffusion of knowledge is not immediate but takes some time, both across countries and across sectors.

Furthermore, the results of tests for unit roots are displayed in Table 1. Since data are missing for a few sectors in some years we have an unbalanced panel. Accordingly, the Fisher method, which was proposed by Maddala and Wu (1999), appears suitable. It has the added advantage of flexibility regarding the specification

[9]As the arguments of Zellner, Kmenta and Dreze (1966) hold for an aggregated CD-production function, (6) can be estimated by OLS producing consistent estimates of the parameters.

[10]Estimations showed that the R&D capital stocks are only significant if they enter the estimation with a lag of at least one year. This is in line with the findings of Coe and Helpman (1995) and van Pottelsberghe de la Potterie and Lichtenberg (2001).

of individual effects, individual time trends and individual lengths of time lags in the ADF regressions (Baltagi, 2001, p. 240). The P_λ-statistic is distributed chi-square with $2 \cdot N$ degrees of freedom, where N is the number of panel groups. As Table 1 shows, the tests do not indicate evidence of unit roots, either in the output series $\ln Q_{it}$ or in the factor input series $\ln K_{it}$, $\ln L_{it}$, $\ln M_{it}$ or $\ln W'_{it}$ for the SIM and PIM.[11]

Table 1 about here

The panel nature of our data is taken into account by specifying group-specific fixed-effects, denoted as α_i in eq. (6). Note that our groups refer to industries in different countries, which gives a total (number of industries $\times$ number of countries) of 106 different groups. Hausman tests (not reported) support our fixed-effects specification compared with a random-effects model. Thus, the fixed group-effects appear to be correlated with the explanatory variables. Lagrange-Multiplier (LM) tests (see Godfrey, 1988) based on residuals from eq. (6) reveal that ν_{it} follows an autoregressive process of order 2, i.e.

$$\nu_{it} = \rho_1 \nu_{i,t-1} + \rho_2 \nu_{i,t-2} + \varepsilon_{it}, \qquad \varepsilon_{it} \sim N(0, \sigma^2).$$

Accordingly, a Prais-Winsten transformation of the data was carried out (Baltagi, 2001, p. 84-85). The parameters for ρ_1 and ρ_2 are obtained from an auxiliary regression of the residuals on the lagged residuals and are reported in Tables 2 and 3. To check if the serial correlation of the residuals has been removed, Lagrange-Multiplier (LM) tests on the null hypothesis of no further serial correlation of the residuals have been carried out for all estimations. The test statistic is chi-square distributed with one degree of freedom and has a critical value of 3.84 at the five percent level and one of 6.63 at the one percent level. The diagnostic statistics are reported in Tables 2 and 3. At the one percent level the null of no serial correlation is only rejected for variant C of the PIM in Tables 2 and 3.

[11] Note that since S^D_{it} and S^F_{it} are constructed as linear combinations from W'_{it}, this also automatically leads to a rejection of the unit roots hypotheses for $\ln S^D_{it}$ and $\ln S^F_{it}$.

Due to the additional presence of panel heteroscedasticity, we report results from two different estimation strategies. First, following the arguments of Beck and Katz (1995) who pointed out that – in the case of a small panel – the use of a FGLS estimator produces standard errors which may lead to overconfidence. As our panel consists of 106 groups which have on average about 19 time periods this might be the case. Applying the solution they propose, the results in Table 2 are derived from simple OLS estimation with panel corrected standard errors (PCSE). Second, for testing the sensibility of the results in terms of the used estimation method we repeat the estimation, this time using FGLS with group-specific variances (Greene, 2000, p. 600) producing efficient, i.e. less restrictive, results (Table 3). Comparing the results from these two different estimation approaches enables us to assess the sensitivity of results with respect to the underlying estimation method.

Furthermore, to detect potential multicollinearity problems, the condition number for the matrix $X'X$ of explanatory variables after AR(2) transformation is also reported for each estimation (Judge et al., 1985). Since condition numbers larger than 100 indicate potential multicollinearity among regressors, all estimations appear to suffer from this problem.

Tables 2 and 3 about here

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5 Estimation Results

Tables 2 and 3 contain the estimation results. Fixed group effects α_i are highly statistically significant but are not reported in the interest of brevity.[12] We estimate four variants (A, B, C, D) of the model (6) both for the PIM as well as for the SIM R&D capital stocks. In variant A, only the internal R&D stock $\ln W'_{it}$ is included, and external R&D capital stocks are excluded. In variant B, the domestic R&D stock $\ln S^D_{i,t-1}$ is added. In variant C, both the external domestic $\ln S^D_{i,t-1}$ and external foreign R&D $\ln S^F_{i,t-1}$ stocks are added. In variant D, the external foreign R&D stock $\ln S^F_{i,t-2}$ is lagged by two years instead of one year.

[12]The estimation results of the fixed group effects are available upon request.

The estimations based on the R&D capital stocks constructed by the PIM produce ambiguous results. Using OLS with PCSE (Table 2) it turns out that only in Variant A do all coefficients have the expected sign and significance. In Variants B, C and D, however, the internal R&D capital stock becomes statistically insignificant when the external domestic R&D capital stock (Table 2, Variant B) and the external foreign R&D capital stock are included (Table 2, Variants C and D).

To test if this finding is a result of the applied (restrictive) estimation method we repeat the estimations using FGLS with group-specific variances (Table 3). Although FGLS leads to efficient estimators and thus smaller standard errors than in the case of the OLS regressions the overall picture does not change. Still, the results on the influence of the internal R&D capital stock remain fragile. The stepwise introduction of the one-year lagged external domestic and the external foreign R&D capital stocks results in a statistically insignificant internal R&D capital stock. In contrast to the OLS regression the one-year lagged external foreign R&D capital stock is statistically significant. If the external foreign R&D capital stock is included with a lag of two years, the internal R&D capital stock becomes significant again (Table 3, Variant D). Thus, we have to conclude that the results for the internal R&D capital stock are not robust when external R&D variables are added. This result has been reported in empirical work on spillovers and is usually explained by the existence of multicollinearity among R&D capital stock variables (Mohnen, 1996). However, an examination of the variance decomposition proportions of the characteristic roots (Judge et al., 1985, p. 103) reveals that whereas the time trend and the labor variable are affected particularly strongly by multicollinearity, the two external R&D capital stocks and the internal R&D capital stock are affected less. In addition, the fact that there are only low partial correlations between the various R&D capital stocks supports the presumption that multicollinearity is not the reason for the insignificance of the internal R&D capital stock. This raises the question of how this result should be interpreted. Since it is not plausible that internal R&D does not have any effect on output, further doubts are cast on the PIM's suitability as a method for constructing R&D capital stocks.

The estimations based on our SIM-constructed R&D capital stocks yield more plausible and robust results. The internal R&D capital stock is significant for all variants in Tables 2 and 3, and the results are more robust against variations in the model structure. While the external domestic R&D capital stock is highly significant when included with a lag of one year, the external foreign R&D capital stock becomes significant in Table 3 when it enters the equation with a lag of two years. These results are plausible considering that the diffusion of knowledge is usually faster within a country than between countries. Although the reported condition numbers again indicate a potential multicollinearity problem for the SIM as well, we do not find a serious effect on the estimation results. In sum, Tables 2 and 3 show that the results for SIM are robust and that the coefficients have reasonable magnitudes. In contrast to a number of other studies (Mohnen, 1996), the estimated output elasticities do not imply extraordinarily high returns, either from internal or from external R&D. The rate of return with an increase in the internal R&D capital stock of one USD dollar is, for instance, about 0.3719 USD in variant D of the SIM, and with an additional increase in the external domestic R&D capital stock of one USD, the rate of return is 0.0626 USD. The rate of return on an increase in the external foreign R&D capital stock of one USD is 0.0007 USD.

6 Conclusions

In this paper, we compared a new method for constructing R&D capital stocks suggested in Bitzer (2005) with the usually applied perpetual inventory method (PIM). The new method is based on less restrictive assumptions than the commonly used PIM, abandoning the restrictive assumption of a constant depreciation rate. Following the idea of Schumpeter, the development of the R&D capital stock is modelled as a process of creative destruction taking into account that newly generated knowledge not only adds to the R&D capital stock but also displaces old knowledge, and therefore destroys a part of the R&D capital stock. The depreciation of the R&D capital stock is thus connected to past investments in R&D resulting in a depreciation rate which varies over time.

A direct comparison of the PIM and the new method based on industry data of twelve OECD countries shows that the R&D capital stock variable constructed with the SIM leads to more plausible and also more robust results. While the use of the PIM leads to insignificant coefficients for the internal R&D capital stock if external R&D capital is introduced into the estimations, in the case of the SIM, the internal R&D capital stock is significant throughout all model variations. Additional tests show that the bad performance of the PIM cannot be attributed to multicolinearity issues between the different R&D capital stocks, nor is it the result of the estimation method used.

Further research is required to analyse how the substitution rate of new knowledge develops over time. The determination of sector- or country-specific substitution rates should also be placed high on the agenda for future research.

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Appendix

Data description

The estimations have been carried out on the basis of data for nine manufacturing industries in the twelve OECD countries Canada, Denmark, Finland, France, Italy, Japan, Netherlands, Norway, Sweden, the United Kingdom, the USA, and West Germany. The data were taken from the OECD databases ANBERD and STAN. The data can be found in the ISIC Rev. 2 classification for the years 1973 to 1997. The length of the available time series differs between the countries and the panel is therefore unbalanced. The data has been deflated to constant prices of 1990 with the OECD value-added deflator. Thereafter it was converted into USD using the exchange rates from 1990. Exchange rates are more suitable in this case than Purchasing Power Parities, because the latter are oriented more towards consumption.

¿From this data, output Q is measured as gross production, private capital K is calculated from annual investments using the PIM and assuming a depreciation rate of 10 percent, labor L is measured as the number of employees, and material / intermediate inputs M are calculated as the difference between gross output and value-added.

Tables

Table 1: Results for the Fisher-type Unit Root Test for Panel Data

Variable	P_λ-statistic	p-value
$\ln Q$	288.8	0.0000
$\ln K$	412.5	0.0000
$\ln L$	307.4	0.0000
$\ln M$	322.6	0.0000
$\ln W_{PIM}$	512.2	0.0000
$\ln W'_{SIM}$	563.5	0.0000

Table 2: OLS with PCSE Estimation Results

Dep. var.	**Lag**	**PIM**				**SIM**			
$\ln(Q/L)$	**years**	**Variant A**	**Variant B**	**Variant C**	**Variant D**	**Variant A**	**Variant B**	**Variant C**	**Variant D**
$\ln(W'/L)$	1	.0180***	.0070	.0064	.0068	.0125***	.0056*	.0055*	.0077*
		(.0046)	(.0047)	(.0046)	(.0046)	(.0029)	(.0029)	(.0028)	(.0041)
$\ln(S^D/L)$	1	—	.0420***	.0314***	.0357***	—	.0413***	.0398***	.0385***
		—	(.0084)	(.0092)	(.0085)	—	(.0081)	(.0091)	(.0086)
$\ln(S^F/L)$	1	—	—	.0159	—	—	—	.0030	—
		—	—	(.0099)	—	—	—	(.0093)	—
	2	—	—	—	.0158*	—	—	—	.0107
		—	—	—	(.0090)	—	—	—	(.0086)
$\ln(K/L)$	-	.0550***	.0649***	.0662***	.0729***	.0573***	.0661***	.0663***	.0723***
		(.0102)	(.0102)	(.0102)	(.0106)	(.0101)	(.0102)	(.0102)	(.0105)
$\ln L$	-	-.0485***	-.0240**	-.0162	-.0128	-.0502***	-.0225*	-.0213*	-.0143
		(.0100)	(.0116)	(.0125)	(.0127)	(.0099)	(.0115)	(.0123)	(.0125)
$\ln(M/L)$	-	.7766***	.7752***	.7758***	.7745***	.7774***	.7752***	.7752***	.7743***
		(.0049)	(.0049)	(.0049)	(.0051)	(.0049)	(.0049)	(.0049)	(.0051)
Year	-	.0025***	.0007**	.0003	.0000	.0027***	.0008*	.0007	.0003
		(.0003)	(.0005)	(.0005)	(.0006)	(.0003)	(.0004)	(.0005)	(.0005)
ρ_1		.9151	.8981	.8738	.8749	.9143	.8976	.8950	.8848
ρ_2		-.1572	-.1436	-.1213	-.1507	-.1592	-.1462	-.1435	-.1609
LM-Test		3.80	4.43	8.87	5.82	4.43	4.86	5.49	4.81
Condition no.		1547	2520	2854	3437	1477	2397	2674	3179
adj. R^2†		.9735	.9682	.9707	.9701	.9732	.9651	.9659	.9701
Obs.		2114	2114	2114	2008	2114	2114	2114	2008

Remarks: Panel Corrected Standard Errors (PCSE, see Beck and Katz 1995) are given in parentheses.
Group-specific effects (α_i) are not reported. ***, **, * indicate a significance at the 1%, 5% and 10% levels, respectively.
†R^2 values from the untransformed model.

Table 3: FGLS Estimation Results

Dep. var. $\ln(Q/L)$	Lag years	PIM Variant A	PIM Variant B	PIM Variant C	PIM Variant D	SIM Variant A	SIM Variant B	SIM Variant C	SIM Variant D
$\ln(W'/L)$	1	.0168***	.0043	.0044	.0054*	.0078***	.0033**	.0034**	.0062***
		(.0032)	(.0032)	(.0046)	(.0032)	(.0019)	(.0015)	(.0015)	(.0022)
$\ln(S^D/L)$	1	—	.0420***	.0364***	.0373***	—	.0424***	.0422***	.0385***
		—	(.0062)	(.0069)	(.0063)	—	(.0057)	(.0064)	(.0060)
$\ln(S^F/L)$	1	—	—	.0124*	—	—	—	.0000	—
		—	—	(.0074)	—	—	—	(.0067)	—
	2	—	—	—	.0208***	—	—	—	.0128**
		—	—	—	(.0066)	—	—	—	(.0062)
$\ln(K/L)$	-	.0507***	.0588***	.0597***	.0656***	.0520***	.0578***	.0578***	.0619***
		(.0071)	(.0069)	(.0069)	(.0069)	(.0070)	(.0068)	(.0068)	(.0069)
$\ln L$	-	-.0412***	-.0160*	-.0100	-.0036	-.0479***	-.0182**	-.0183**	-.0098
		(.0078)	(.0085)	(.0091)	(.0091)	(.0076)	(.0084)	(.0089)	(.0090)
$\ln(M/L)$	-	.7802***	.7790***	.7791***	.7787***	.7815***	.7789***	.7789***	.7792***
		(.0037)	(.0036)	(.0036)	(.0047)	(.0035)	(.0036)	(.0036)	(.0036)
Year	-	.0025***	.0006*	.0003	-.0002	.0028***	.0009**	.0009**	.0003
		(.0002)	(.0003)	(.0004)	(.0004)	(.0002)	(.0003)	(.0003)	(.0004)
ρ_1		.9151	.8981	.8738	.8749	.9143	.8976	.8950	.8848
ρ_2		-.1572	-.1436	-.1213	-.1507	-.1592	-.1462	-.1435	-.1609
LM-Test		3.80	4.43	8.87	5.82	4.43	4.86	5.49	4.81
Condition no.		1547	2520	2854	3437	1477	2397	2674	3179
adj. R^2†		.9735	.9682	.9707	.9701	.9732	.9651	.9659	.9701
Obs.		2114	2114	2114	2008	2114	2114	2114	2008

Remarks: Standard errors are given in parentheses. Group-specific effects (α_i) are not reported.
***, **, * indicate a significance at the 1%, 5% and 10% levels, respectively. †R^2 values from the untransformed model.